A High-performance Structural Material Based on Maize Straw and Its Completely Biodegradable Composites of Poly (Propylene Carbonate)

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Research Article

Keywords: Densified maize straw, high-performance, chemical treatment, hot pressing, poly (propylene carbonate)

Posted Date: May 27th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-486898/v1

Abstract

A technique of chemical treatment combined with hot pressing is used to fabricate a high-performance structural material based on maize straw. The chemical structures and compositions of the densified maize straw are determined by ATR-FTIR, XRD, and TGA. The tensile strength and elongation at break of the densified straw can reach as high as 598.6MPa and 6.2%, which are approximately 9.3 times and 2.2 times higher than that of the natural straw, respectively. Furthermore, chemical treatment and hot pressing are essential steps for preparing the densified straw. The chemical treatment using a mixed alkali solution can remove the fractional lignin and hemicellulose but preserve most of the cellulose, thus enhancing the degree of crystallinity and the heating resistance of the densified straw. The SEM results prove that densification by hot pressing is committed to fabricating a structure material with high-performance from maize straw, which has eliminated the defects and reinforced the mechanical properties of the densified straw. At the molecular level, the hydrogen bonds between the aligned cellulose fibers have bridged the neighboring cellulose fibers, reinforcing the mechanical properties of the densified straw. After compositing the densified straw with a biodegradable poly (propylene carbonate), the mechanical properties of the composite are considerably improved, predicting a huge application prospect in automobile, construction, furniture, and even airplane fields.

1. Introduction

The development of sustainable materials is extremely important to meet the growing global demand for energy-saving materials and reduce negative environmental consequences.(Benítez et al. 2017) Simultaneously, the industrial community is also looking for lightweight integrated with high strength and toughness materials.(Ritchie 2011) Maize is one of the most important crops in the world.(X. Wang et al. 2021) A huge number of maize straws as crop residue is yielded every year, accompanying the great needs of maize. Although maize straws have been partly utilized(Croce et al. 2016) in biochar application, many maize straws are still wasted in burned(Xu et al. 2021) and mulched. The burned maize straws lead to environmental pollution and eventually cause a significant waste of natural resources. Thus, how to entirely utilize maize straw as a sustainable material is not only a scientific problem but also a societal issue. Up to now, maize straw has been used in the areas of chemical (S. Chen et al. 2018; Lopez-Hidalgo et al. 2021; Ma et al. 2018) and biological engineering(Xiao Han et al. 2018; Pan et al. 2016), energy(Du et al. 2020; Zabed et al. 2016), composite materials(Tarres et al. 2020), and so on. For example, forage, fertilizer, bioethanol, furaldehyde et al. can be produced from maize straws. In this study, we focus on solving the issue of maize straw for a lightweight and sustainable material through a process of waste-to-energy.

Maize straw composited with polymers is a general method for biochar application. Some researchers had reported that the composite materials were fabricated from polyethylene(Tarres et al. 2020) and polypropylene(Delgado-Aguilar et al. 2018) reinforced with maize straw. In general, maize straws as a filler, its strength, and modulus determine the mechanical properties of the resulting composite(Ku et al. 2011; Pickering et al. 2016). Therefore, enhancing the strength and modulus of maize straw is quite

important for fabricating high-performance polymer/maize straw composite. The mechanical performance of biomass materials such as natural wood and bamboo can be enhanced by pre-treatment with chemicals (G. Chen et al. 2020; Frey et al. 2018; Kabir et al. 2012; Mi et al. 2020; Y. Y. Wang et al. 2021), steam(Fang et al. 2011), heat(Fang et al. 2011; Poletto et al. 2014), bleaching and caramelization(Sharma et al. 2015), or by filling with resin followed by densification(Kalali et al. 2019). Recently, Hu and his coworkers(Song et al. 2018) reported a simple and effective strategy via chemical treatment followed by hot-pressing to directly transform bulk natural wood into a high-performance material with a more than tenfold increase in strength, toughness, and ballistic resistance. A similar method was also used to enhance the performance of bamboo(Li et al. 2020). The tensile strength and modulus for the densified bamboo could reach as high as 1GPa and 75GPa, respectively. As the main biomass material, the mechanical performance of the maize straw is expected to be enhanced using the technique of chemical treatment combined with hot-pressing.

Poly (propylene carbonate) (PPC) is a kind of aliphatic polycarbonate synthesized from propylene oxide and carbon dioxide(Y. Chen et al. 2013; Wang E 2020). PPC is one of the most promising environment-friendly and degradable synthetic polymeric material that has been widely applied in the fields of film, barrier, and biomedical materials(Muthuraj et al. 2018; Qin et al. 2015). In order to enhance its thermal and mechanical properties, PPC has been composited with carbon fiber(W. Wang et al. 2020), wood(Nörnberg et al. 2014), SiC nanowires(Qu et al. 2020), and micro-fibrillated cellulose(Qi et al. 2014). Previously, chlorinated PPC (CPPC) was used to improve the mechanical properties of PPC/straw flour composites(Bin 2017). The tensile strength was increased by 38% when the mass ratio of straw flour and CPPC was 30% and 1.8%, respectively. Hence, further improving the mechanical properties of PPC/maize straw composites and increasing the ratio of maize straw in composites for cost savings are the two significant issues in the application of the PPC industry.

In this study, a lightweight integrated with superstrength, high modulus, and toughness densified maize straw was fabricated via chemical treatment combined with hot pressing. Different treatments, including chemical treatment, cold and hot pressing, and chemical treatment combined with hot pressing, were individually evaluated. The chemical structures and compositions of the densified maize straw were determined by ATR-FTIR, XRD, and TGA. Combined with the analysis of surface microstructures by SEM, the reinforced mechanism of the densified maize straw was further discussed and proposed a mechanism of the compaction of voids in vertical and the alignment of cellulose microfibrils in horizontal. Moreover, the densified maize straw was applied to improve the mechanical properties of PPC/densified maize straw composites.

2. Experiment

2.1 Materials and chemicals.

The raw (natural maize straw peel) was peeled from maize straws by hands taken from the southern suburb of Changchun City, Jilin Province, China. Poly (propylene carbonate) (PPC) was obtained from

Taizhou Bangfeng Plastic Co., Ltd. (Wenling, Zhejiang, China). Sodium hydroxide (NaOH, AR) and sodium sulfite (Na_2SO_3, AR) were obtained from Beijing Chemical Co., China.

2.2 Sample preparation

Densified maize straw:

In the beginning, the natural maize straw was treated by a mixed solution (2.5mol/L NaOH and 0.4mol/L Na_2SO_3) at 80°C for 0.5h to partially remove hemicellulose and partly lignin. Next, it was cleaned by ultrasonic for 15mins and then immersed into the deionized water for 2h to remove the residual lye as much as possible. After air-drying for a week, the samples were compressed under the pressure of 8MPa at 100°C for 0.5h to make it densification. The densified maize straw was obtained.

Compressed maize straw

The compressed maize straw was obtained directly by hot pressing under the pressure of 8MPa at 100°C for 0.5h.

Modified maize straw

The modified maize straw was obtained with the chemical pre-treatment but without hot pressing.

PPC/maize straw composite:

At first, the densified maize straw was cut up into approximately 5mm-long fragments along the growth direction of the aligned vascular fibers. Then, the straw fragments were smashed into powder by a grinder to separate the vascular fibers. The mixture of PPC/densified maize straw was prepared as a certain mass ratio of 60/40. Next, the prepared mixture of PPC/densified maize straw was blended in a torque rheometer (XSS-300, Shanghai Kechuang Rubber Plastic Mechanical Equipment Co., Ltd, China) at 50rpm for 7min. At last, after compression molding under pressure of 8MPa at 100°C for 0.5h, the PPC/densified maize straw composite board (120mm·100mm·2mm) was obtained. By this method, PPC/natural maize straw composites, PPC/modified maize straw composites, and PPC/compressed maize straw composites were fabricated, respectively. It is noted that the composite boards were all cut into strips (50mm·10mm·2mm) for mechanical tests.

2.3 Mechanical test

Tensile test

During testing, the samples were clamped at both ends and stretched along the longitudinal direction of samples till the sample fractured with a constant test speed of 5mm/min at room temperature. Due to the limitation of the raw material, the length, width, and thickness of the test samples of natural, modified, compressed, and densified maize straw were 100mm, ≈3mm, and ≈ 0.3mm, respectively. The size of the test samples of neat PPC and PPC/natural maize straw composites, PPC/modified maize straw

composites, PPC/compressed maize straw composites, PPC/densified maize straw composites was 50mm·10mm·2mm. All tests were conducted on the Instron 1121 Material Testing Machine, according to GB/T 1040.2–2006 (China national standard).

Three points bending test

The size of the test samples of PPC/natural maize straw composites, PPC/modified maize straw composites, PPC/compressed maize straw composites, and PPC/densified maize straw composites was 50mm·10mm·2mm. The span between the two bottom rollers was 20mm, and the speed of the top roller pressing down was 2mm/min. All tests were performed on the Instron 1121 Material Testing Machine, according to GB/T9341-2000 (China national standard).

2.4 Scanning electron microscope (SEM)

Cross-section of the natural and densified maize straw

The natural maize straw and densified maize straw were first placed in liquid nitrogen for 30 mins. After fracturing the samples quickly, the test samples of natural and densified maize straw were obtained. Then, the microstructure of the cross-section of natural and densified maize straw with spraying gold were observed through a Field Emission Scanning Electron Microscope (FEG ESEM) (XL30, FEI COMPANY) at an acceleration voltage of 5kV.

Side face of the natural and densified maize straw

The test samples were directly peeled from the natural and densified maize straw by hands. Then, the side face of the natural and densified maize straw with spraying gold could be observed.

The surface of the natural and densified maize straw

The waxy layer of the natural maize straw must be removed before observing the surface of the natural maize straw. However, due to the waxy layer had been removed, the surface of densified maize straw with spraying gold could be observed directly.

2.5 X-ray Diffraction (XRD)

Before the test, the natural and densified maize straw were grinded into powder. The XRD curve was obtained by a Wide-angle X-ray Diffractometer (D8 ADVANCE, BRUKER Co., Germany) (operating voltage at 40kV, current at 40mA, CuKα, λ = 0.154nm) and the scanning angle was from 5° to 40°.

2.6 Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy (ATR-FTIR)

Before the test, the natural and densified maize straw were first grinded into powder. The powder was compressed into a sheet at room temperature. Then, the test samples of natural and densified maize

straw were obtained. All tests were performed using a Fourier transform infrared spectrometer (BRUKER, ALPHA, PLATINUM-ATR) from 500cm^{-1} to 4000cm^{-1} at a spectral resolution of 4cm^{-1} with a total of 32 scans.

2.7 Thermogravimetric Analysis (TGA) and Derivative Thermogravimetry (DTG)

The tests were performed on a thermal analysis instrument (TA Instruments Q50, USA) from room temperature to 600°C at a rate of 10 K·min^{-1} under a nitrogen atmosphere. Then, the statistics of TGA and DTG could be obtained directly.

3. Results And Discussion

To fabricate a kind of high-performance biomass material based on natural maize straw, a chemical treatment technology combined with hot pressing is used to obtain densified maize straw. The chemical treatment by a mixed alkali solution is used to remove the hemicellulose and lignin, called delignification. The hot pressing at a certain condition, called densification, is applied to increase the number of loading fiber per unit volume and eliminate internal defects of the sample. The scheme of processing approach to transforming the natural maize straw into the densified maize straw is presented in Scheme 1. The natural, chemical modified, compressed without chemical treatment, and compressed with chemical treatment maize straw can be simplified as natural straw (NS), modified straw (MS), compressed straw (CS), and densified straw (DS), respectively.

3.1 The lightweight densified straw with superstrength and high modulus and toughness

The mechanical performance of the natural, modified, compressed, and densified straw is shown in Fig. 1. For better comparison, the tensile strength-strain curve was selected instead of the typical stress-strain curve (Fig. S1) due to the different cross-sectional areas of the tested samples. The tensile strength of the four samples in Fig. 1a is proportional to the strain, which means the stress and the strain are linearly related before fracture. Correspondingly, the tensile strength and elongation at break of the densified straw are enhanced simultaneously (Fig. 1b and 1c). Notably, the tensile strength and elongation at break of the densified straw have reached 598.6MPa and 6.2%, which is approximately 9.3 times and 2.2 times higher than that of the natural straw, respectively. The superstrength and the great elongation at break of the densified straw is the highlight of this study and can be comparable with the work of the densified wood and bamboo. Other researchers have reported that the tensile strength of the densified wood (≈ 549MPa) and the densified bamboo (≈ 770MPa) are both dramatically enhanced relative to the tensile strength of the natural wood (≈ 47MPa) and the natural bamboo (≈ 298MPa), respectively(Li et al. 2020; Song et al. 2018). However, the elongation at break of the densified wood (≈ 1.3%) and densified bamboo (≈ 1.8%) in those studies have no obvious changes after treatment. These

discussions suggest that the tensile strength and elongation at break of the nature maize straw can be simultaneously and tremendously improved by the chemical treatment combined with hot pressing.

In addition, Young's modulus of the densified straw has reached to 16.6GPa that is about 5.9 times higher than that of the natural straw (Fig. 1d). The specific strength of the densified straw has reached to 434MPa·g^{-1}·cm^3 that is almost 3.0 times higher than that of the natural straw (Fig. 1e), and the density of the densified straw has increased about two times after hot pressing (Fig. 1f). Therefore, the mechanical properties of densified straw with high-performance can compete with the mechanical properties of aluminum alloy. Generally, aluminum alloy is widely used in various fields due to the lightweight and high specific strength. In comparison, four different industrial aluminum alloys are used to evaluate the superiority of the densified straw. Astonishingly, the tensile strength of the densified straw (598.6MPa) is completely higher than that of 5052-H112 (175MPa), 6061-T6 (290MPa), 2024-T3 (440MPa), and even the aircraft-grade aluminum alloy 7075-T6 (540MPa). For lightweight, the specific strength of the densified straw (434MPa·g^{-1}·cm^3) is also higher than that of 5052-H112 (64MPa·g^{-1}·cm^3), 6061-T6 (106MPa·g^{-1}·cm^3), 2024-T3 (156MPa·g^{-1}·cm^3), and even 7075-T6 (191MPa·g^{-1}·cm^3). Moreover, the pictures of the bending of the natural and densified straws are shown in Fig. 2. Clearly, the natural straw can be easily broken in a relatively small bending angle (Fig. 2b), while the densified straw can be bend into a circle but not broken (Fig. 2d). This phenomenon suggests that the densified straw still possesses excellent bending toughness after chemical treatment followed by hot pressing.

Above all, a lightweight and sustainable densified straw with excellent mechanical properties is fabricated by chemical treatment combined with hot pressing. The tensile strength and specific strength of the densified straw are even higher than those of the commercial aluminum alloys, predicting a promising application as a lightweight material in the fields of automobile, construction, furniture, and even airplane.

3.2 Effect of different processing methods on tensile strength and modulus.

The high-performance densified straw in this work was fabricated by chemical treatment combined with hot pressing. Figure 3 shows the tensile strength and modulus of chemical treatment, cold pressing, hot pressing, and chemical treatment combined with hot pressing on natural straw. As a comparison, the performance of natural straw as a control experiment. The properties of natural straw are largely improved after different treatments that significantly affect the properties of tensile strength and Young's modulus. Obviously, chemical treatment combined with hot pressing has the greatest tensile strength and modulus, while none of the separate methods, such as chemical treatment, cold pressing, and hot pressing, can achieve best. These results give us a clear conclusion that the technique of chemical treatment and hot pressing are essential steps for preparing the densified straw.

3.3 The compositions and structural characterizations of natural and densified straws.

Since the densified straw had superior mechanical performance compared to the natural straw, the compositions and structures of the densified straw were characterized. Figure 4a shows the ATR-FTIR spectra of the natural and densified straws. The absorption peaks at around 1507cm^{-1} and 1604cm^{-1} are attributed to the aromatic ring vibrations of the lignin, and the absorption peak at around 1238cm^{-1} is attributed to the C-O-C stretching of aromatic ether linkages of the lignin(Poletto et al. 2014; Rehman et al. 2013). These three peaks at around 1238cm^{-1}, 1507cm^{-1}, and 1604cm^{-1} of the densified straw become weak, which is attributed to the partial removal of lignin after chemical treatment. Besides, the peak at 1732cm^{-1} of the densified straw is almost disappeared, which is due to the disappearance of C = O linkage in hemicellulose, suggesting that the hemicellulose in the natural straw is nearly removed after chemical treatment. The peak of cellulose at 1420cm^{-1} is still reserved in the densified straw, and the hydroxy groups and hydrogen bonds at 3320 cm^{-1} are also preserved in the densified straw. The natural straw is mainly composed of abundant cellulose, hemicellulose, and lignin.(He et al. 2020; Kambli et al. 2017; Sirviö et al. 2017) Theoretically, lye can dissolve lignin and hemicellulose but not cellulose. Thus, the partial lignin and hemicellulose of the natural straw can be easily removed by a mixed alkali solution(Song et al. 2018). Finally, the cellulose can be mostly reserved in the densified straw.

Moreover, the XRD pattern is used to check the crystalline cellulose of the natural and densified straws in Fig. 4b. Cellulose contains crystalline and amorphous phases connected with intra- and inter-molecular hydrogen bonds, whereas hemicellulose and lignin are amorphous.(Nishiyama et al. 2002; Poletto et al. 2014; Reddy et al. 2005; Rehman et al. 2013; Szczęśniak et al. 2020; J. Wang et al. 2021; Ye et al. 2020) Thus, the most preserved cellulose in the densified straw plays a vital role in mechanical properties, especially for the crystalline cellulose. (Benítez et al. 2017) The Segal method is selected to calculate the degree of crystallinity of the natural and densified straws, which assumes that the peak intensity I_{200} is contributed by the crystalline cellulose and amorphous regions, while the peak intensity I_{AM} is entirely contributed by the amorphous regions. (Poletto et al. 2014; Rehman et al. 2013; Thygesen et al. 2005; Q. Wang et al. 2013) Thus, the degree of crystallinity of the cellulose can be calculated as followed.

$$x_C = \frac{I_{200} - I_{AM}}{I_{200}}$$

The calculated degree of crystallinity of the cellulose in the natural and densified straw is 48.6% and 62.3%, respectively. Clearly, the degree of crystallinity of the densified straw is greater than that of the natural straw.

For studying the heating resistance, the TGA and DTG of the natural, modified, compressed, and densified straws are shown in Fig. 4c and 4d. The reported degradation temperature of cellulose (315–400°C), hemicellulose (220–315°C), and lignin (150–900°C) are different.(Yang et al. 2007) In Fig. 4c, the initial degradation temperatures of the modified (314.7°C) and the densified (308.0°C) straws are higher than those of the natural (287.9°C) and the compressed (288.0°C) straws. Besides, the temperatures of the maximum degradation rate of the modified and densified straws are also obviously higher than those of

the natural and compressed straws (Fig. 4d). Thus, chemical treatment using lye but not hot pressing to the natural straw can improve the heating resistance of the modified and the densified straws because of the removal of the partial lignin and hemicellulose and the reservation of the cellulose. In summary, the structures and compositions of the densified straw suggest that the chemical treatment using a mixed alkali solution can remove the fractional lignin and hemicellulose but preserve most of the cellulose, thus enhancing the degree of crystallinity and the heating resistance of the densified straw.

3.4 The microstructures of the natural and densified straws

The appearance of the natural straw and densified straw is shown in Fig. 5a and 5b, respectively. For studying the microstructures of the natural and densified straws, the SEM images of the natural and densified straws in three different directions are shown in Fig. 5c-5n. In the direction of cross-section (TW plane), plenty of holes exist on the cross-section of the natural straw (Fig. 5c and 5d). However, the holes in the cross-section of the densified straw (Fig. 5e) are collapsed, and the cell walls are tightly intertwined with each other, leading to the formation of the complete densified structures (Fig. 5f) in the enlarged image of the densified straw. In the side face, the obvious layer structure and the interstices between layers are presented in images of the natural straw (Fig. 5g and 5h). However, the images of the densified straw show a different view. The interstices among the layers in Fig. 5i become unobservable, and lots of microfibrils are pulled out from the bulk during peeling (Fig. 5j). These morphological changes form a pretty densified and hard-to-peel structure in the side face of the densified straw. Thus, the densification of structures in the cross-section and the side face is the main reason for enhancing density and improving the tensile strength. As mentioned above in Fig. 1, the density of the densified straw increases from 0.43 to 1.38 g cm^{-3}, and the tensile strength is tremendously improved more than ninefold. On the surface perpendicular to the pressure direction, sharply aligned fabric structures are found in the images of the densified straw (Fig. 5m and 5n) compared to the loose and disordered fibers in the images of the natural straw (Fig. 5k and 5i). The aligned cellulose fibers are also contributed to the densified packing, hence improving the mechanical properties of the densified straw in a different direction (Fig. S2). Therefore, microstructural densification is the critical factor to fabricate a structure material with high-performance from maize straw. On the one hand, a densified microstructure helps increase the number of the loading fibers per unit volume and thus obtain a highly compressed material. On the other hand, the processing of densification is an elimination of defects that makes the densified straw more perfect.

3.5 The influence of the pressure on the mechanical properties.

Two steps with chemical treatment and hot pressing can achieve a high-performance structural material based on maize straw. The step of chemical treatment provides an efficient strategy to remove the partial lignin and hemicellulose and preserve the most cellulose, enhancing the crystalline degree and the alignment of the cellulose fibers of the densified straw. The other step, hot pressing, is a technique to perform densification. The influence of the pressure on the mechanical properties of the densified straw is investigated in Fig. 6. The tensile strength (Fig. 6a) and Young’s modulus (Fig. 6c) of the densified straw have the greatest values with the pressure of 8MPa. When the pressure is lower than 8MPa, it is

insufficient to densify and achieve high-performance; while the pressure is higher than 8MPa, the densified and aligned structures probably are slightly destroyed, leading to a bit of decline in strength and modulus. Besides, the elongation at break of the densified straw in Fig. 6b first increases with pressure and then essentially levels off from 6MPa. Hence, for balancing the energy-saving and the mechanical property, 8MPa is the optimum pressure when the temperature is 100°C for 0.5h during hot pressing.

3.6 The reinforced mechanism of the densified straw.

Generally, amorphous hemicellulose and lignin are directly linked to the cellulose microfibrils.(Berglund et al. 2020; Szczęśniak et al. 2020) The scheme of the surface microstructures of the natural straw is shown in Fig. 7a, and the SEM image is below. The microstructures of the natural straw are loose, and lots of small hemicelluloses and lignin patches are linked to the cellulose fibers. After chemical treatment, the patches on the surface of the natural straw are drastically diminished via the removal of the hemicellulose and lignin (Fig. 7b). Lastly, after hot pressing, the densified straw shows a rather compact and ordered microstructure (Fig. 7c and SEM image is below). The surface fibers of the densified straw are recognizable and crosswise arranged, and nearly no mixture of hemicellulose and lignin is found in the SEM image. These results also verify that the two steps combined with chemical treatment and hot pressing have eliminated the defects and reinforced the mechanical properties of the densified straw. Furthermore, the hydrogen bonds between the aligned cellulose fibers (Fig. 7d and 7e) have bridged the neighboring cellulose fibers(Xiaoshuai Han et al. 2019), which is the reinforced mechanism of the densified straw at the molecular level for constructing a structure densified straw with superstrength, high modulus, and extraordinary elongation at break.

3.7 The Composites of PPC and the densified straw.

As aforementioned, the densified straw has been constructed as a structural material with high-performance in tensile and specific strength, modulus, and elongation at a break. Here, the densified straw is used as a filler to reinforce the mechanical properties of the biodegradable PPC and cut costs. The technological process of the PPC and the densified straw composite is shown in Fig. 8a, and the mechanical properties of different samples are presented in Fig. 8b-8e. Taking PPC/densified straw (PPC/DS, 60/40wt%) composite as an example, the densified straw is first blended with PPC in a mixer. After compressing molding, the PPC/DS composite is obtained. The mechanical properties of the PPC/DS composite are improved compared with the sample of the neat PPC and other composites samples. Specifically, the tensile strength and Young's modulus of the PPC/DS composite is 31.9MPa (Fig. 8b) and 1812MPa (Fig. 8d), which is about 157.3% and 124.8% higher than that of the neat PPC, respectively. Moreover, the specific strength and the density of the PPC/DS composite is considerably improved. The densified straw can be used as a reinforced filler with PPC to fabricate a high-performance whole biodegradable composite.

4. Conclusions

In this work, a lightweight densified maize straw with superstrength, high modulus, and toughness based on maize straw peel is successfully fabricated by chemical treatment combined with hot pressing. The tensile strength (598.6MPa) and elongation at break (6.3%) of the densified straw are simultaneously enhanced about 9.3 times and 2.2 times than those of natural maize straw, respectively. The Young's modulus (16.6GPa) of the densified straw is about 5.9 times than that of the natural straw. The tensile strength and specific strength ($434MPa\cdot g^{-1}\cdot cm^{3}$) of the densified straw are even higher than those of the commercial aluminum alloys. The chemical treatment and hot pressing are essential steps for preparing the densified straw and improving the mechanical properties. The chemical treatment using a mixed alkali solution can remove the fractional lignin and hemicellulose but preserve most of the cellulose, thus enhancing the degree of crystallinity and the heating resistance of the densified straw. The densification by hot pressing is committed to fabricating a structure material with high-performance from maize straw, which has eliminated the defects and reinforced the mechanical properties of the densified straw. The microstructural densification in the cross-section and the side face is the main reason for enhancing density and improving the tensile strength. At the molecular level, the hydrogen bonds between the aligned cellulose fibers have bridged the neighboring cellulose fibers, reinforcing the mechanical properties of the densified straw and constructing a structural material with superstrength, high modulus, and extraordinary elongation at break. Lastly, the densified straw is successfully used to composite with PPC for constructing a whole biodegrade material. The mechanical properties of the composite have been reinforced that predicts a huge prospect in automobile, construction, furniture, and even airplane fields. ASSOCIATED CONTENT The stress-strain curve (Fig. S1), the tensile strength, elongation at break, and Young's modulus perpendicular to the growth direction of the natural and densified straw (Fig. S2) are shown in SUPPORTING INFORMATION.

Declarations

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Declarations

Authors' contributions J. Ge conceived and designed the experiments under the guidance of W. Jiang and J. Jin. J. Ge and Y. Gao conducted experimental characterizations. F. Li provided the analysis and discussion for data. The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

Funding This work is financially supported by Jilin Provincial Science and Technology Development Program (20190302090GX and 20200501005GX).

Conflict of interest The authors declare no competing financial interest.

Ethics approval This article does not contain any studies with human paricipants or animals performed by any of the authors.

Consent for publication Consent to publication was obtained from all individual participants included in the study.

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Figures

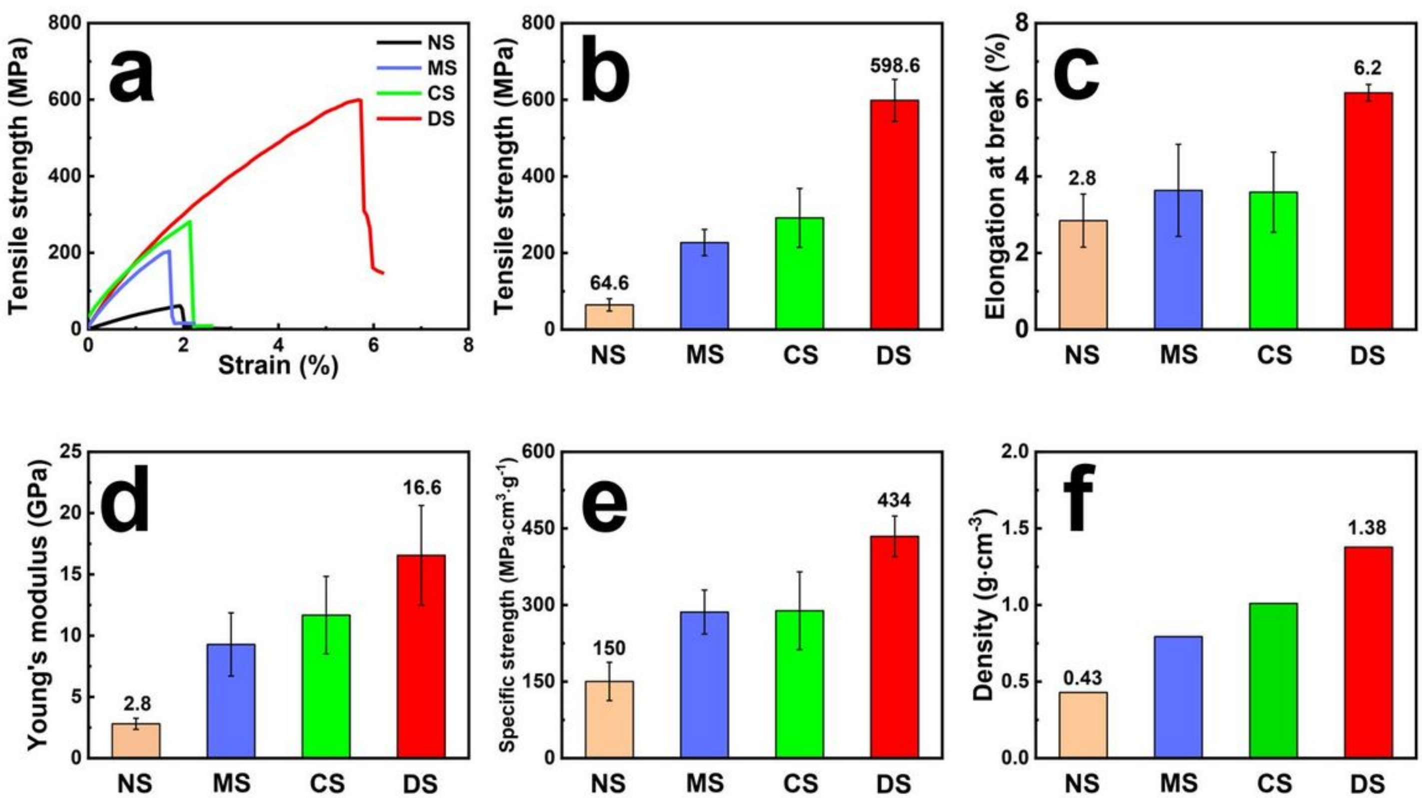

Figure 1

The comparison of the tensile strength-strain curve (a), tensile strength (b), elongation at break (c), Young's modulus (d), specific strength (e), and density (f) of the natural, modified, compressed, and densified straw.

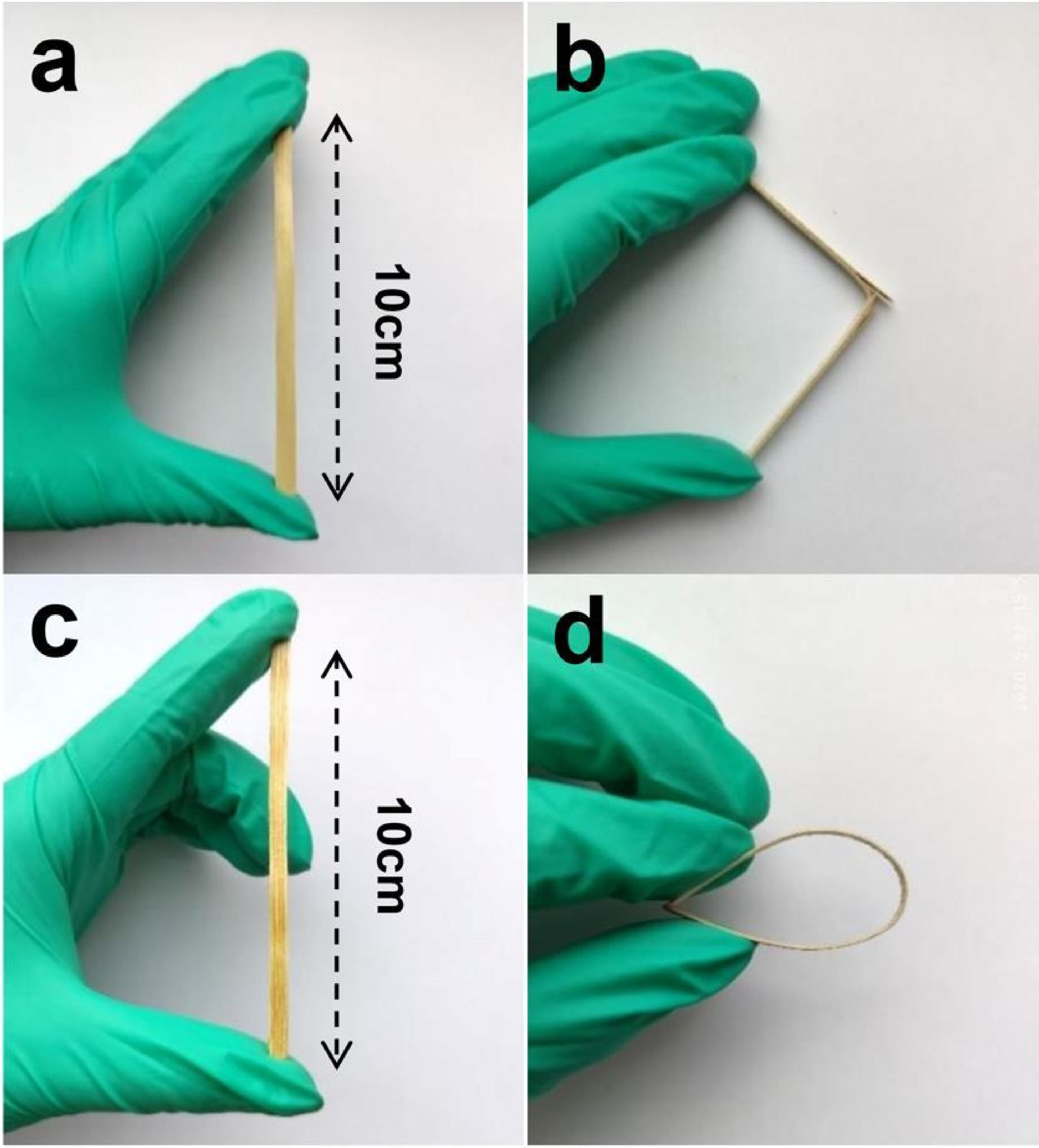

Figure 2

The bending of the natural (a-b) and densified (c-d) straw strips.

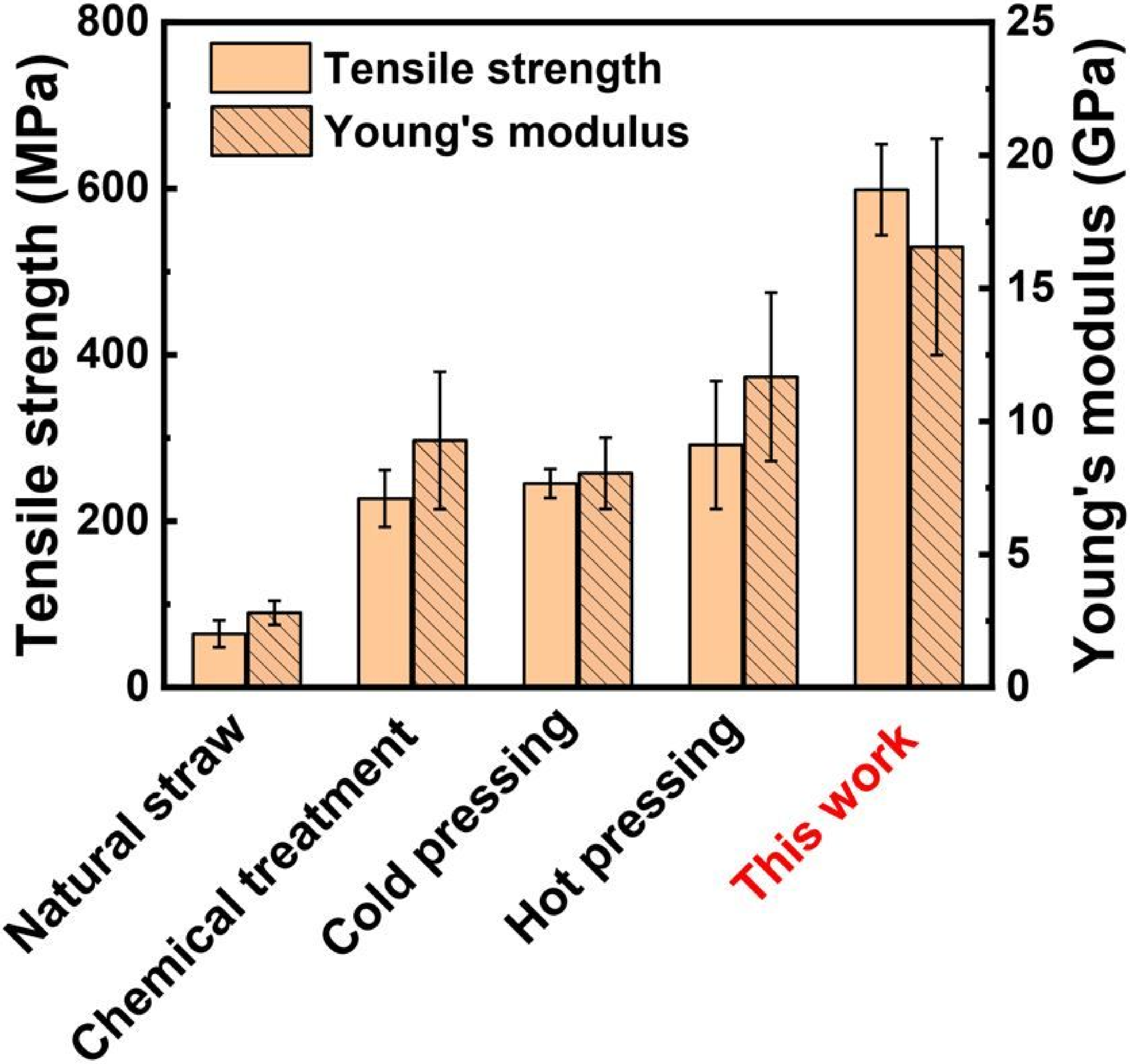

Figure 3

The tensile strength and Young’s modulus of different processing methods on natural straw.

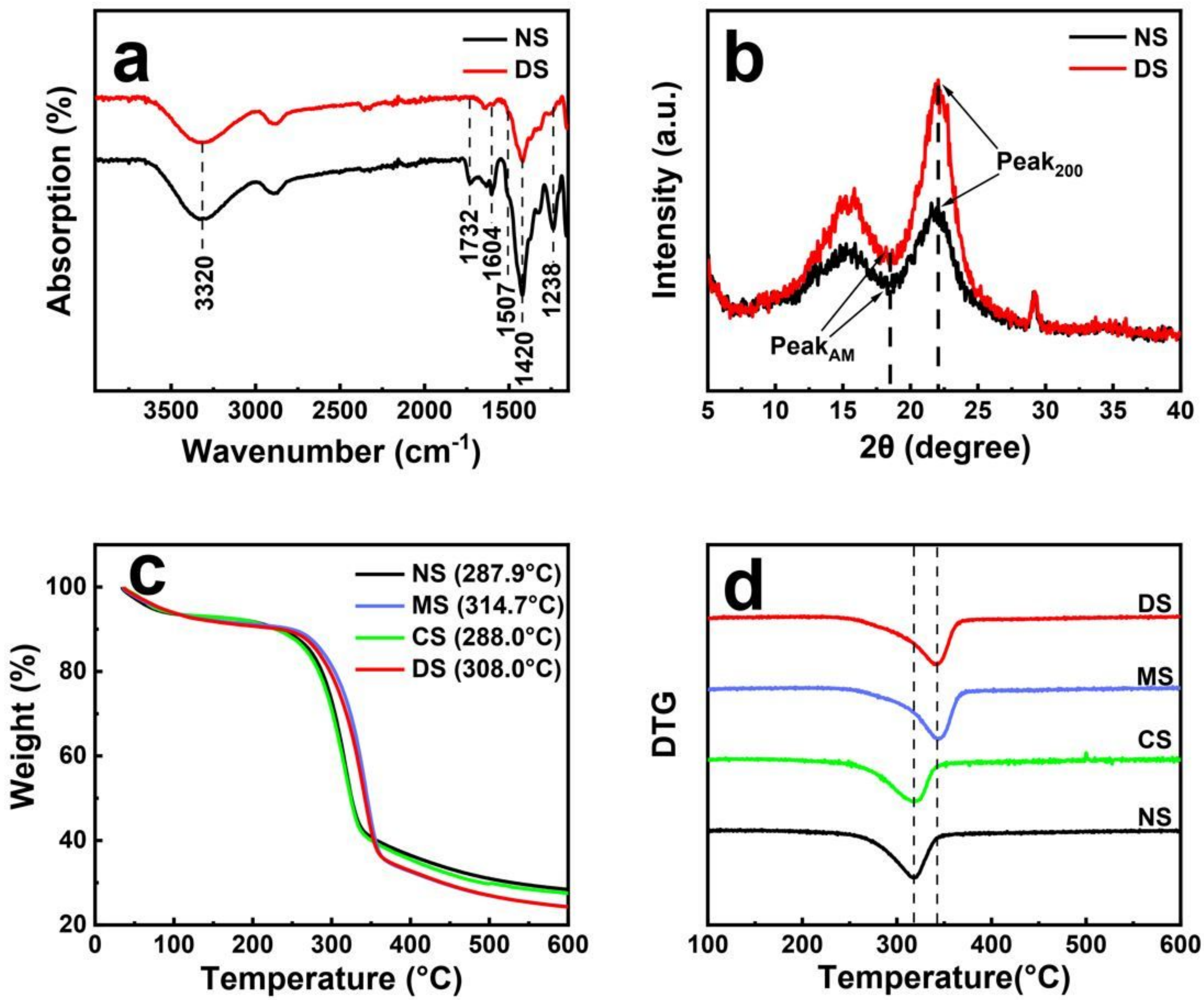

Figure 4

The ATR-FTIR spectra (a) and XRD pattern (b) of natural and densified straw; the TGA (c) and DTG (d) of natural, modified, compressed, and densified straws.

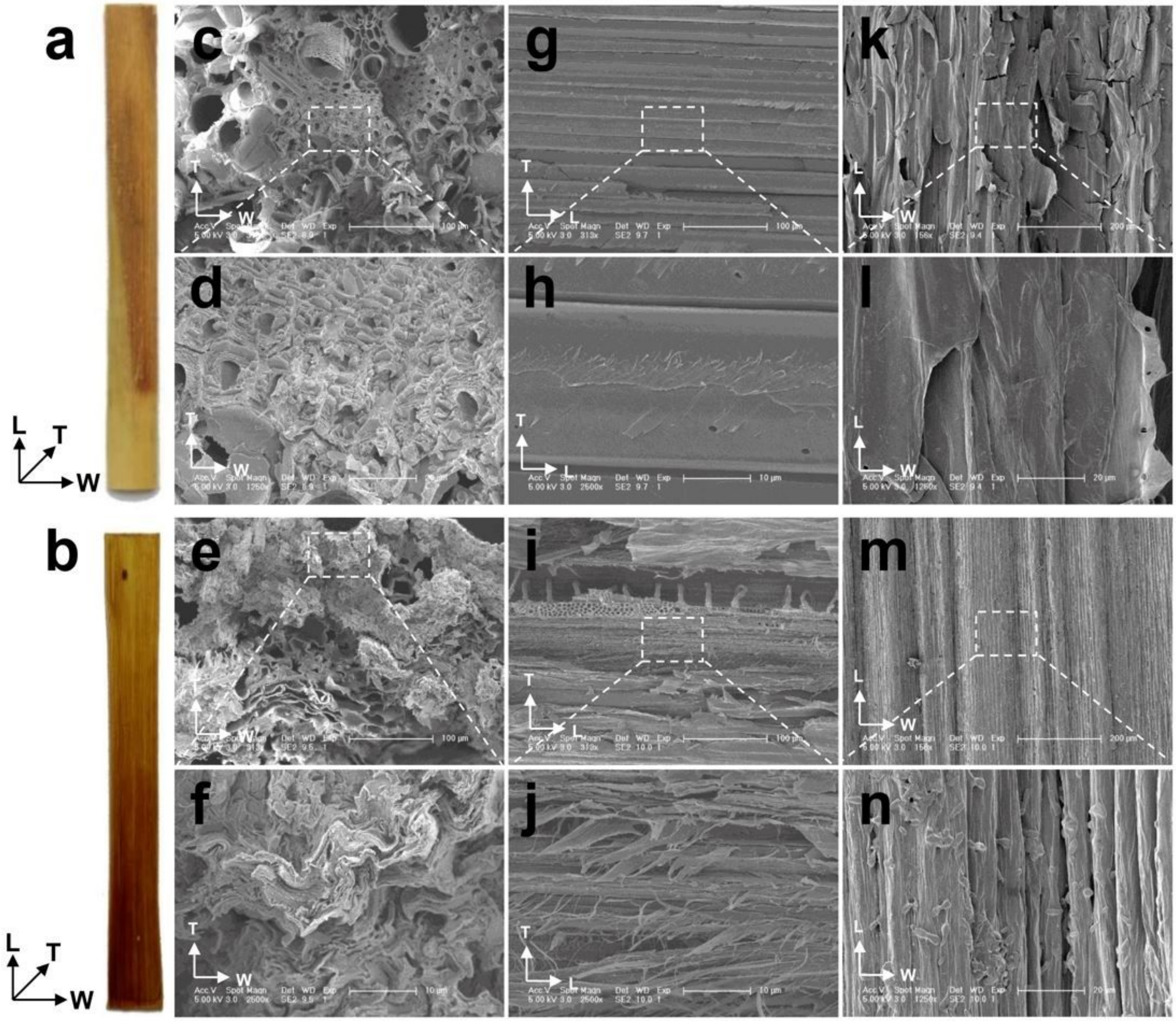

Figure 5

The pictures of the natural straw (a) and densified straw (b); the SEM pictures of the cross-section (in the TW plane) of the natural straw (c, d) and densified straw (e, f), the side face (in the TL plane) of the natural straw (g, h) and densified straw (i, j), the surface (in the LW plane) of the natural straw (k, l) and densified straw (m, n).

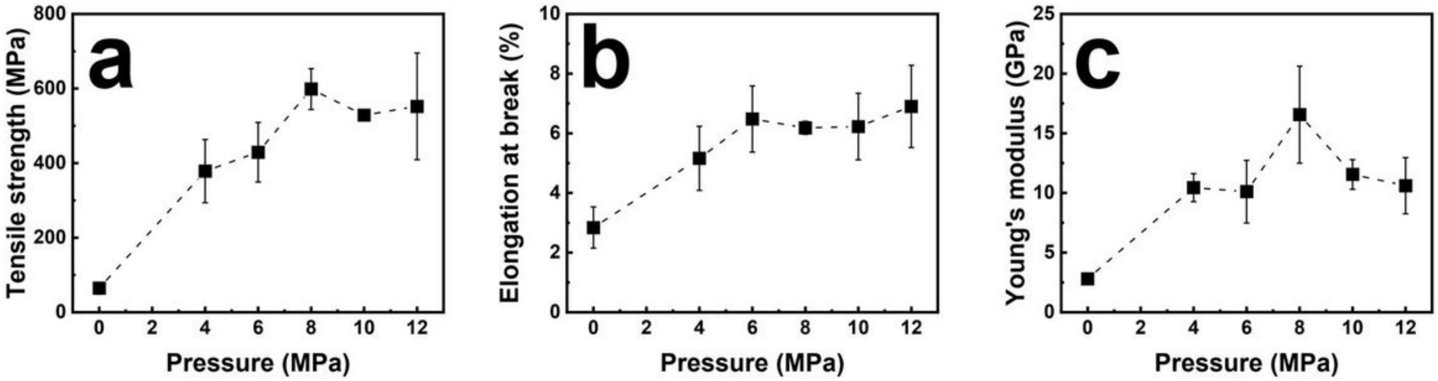

Figure 6

The tensile strength (a), elongation at break (b), and Young's modulus (c) of the samples under different pressure at 100°C for 0.5h.

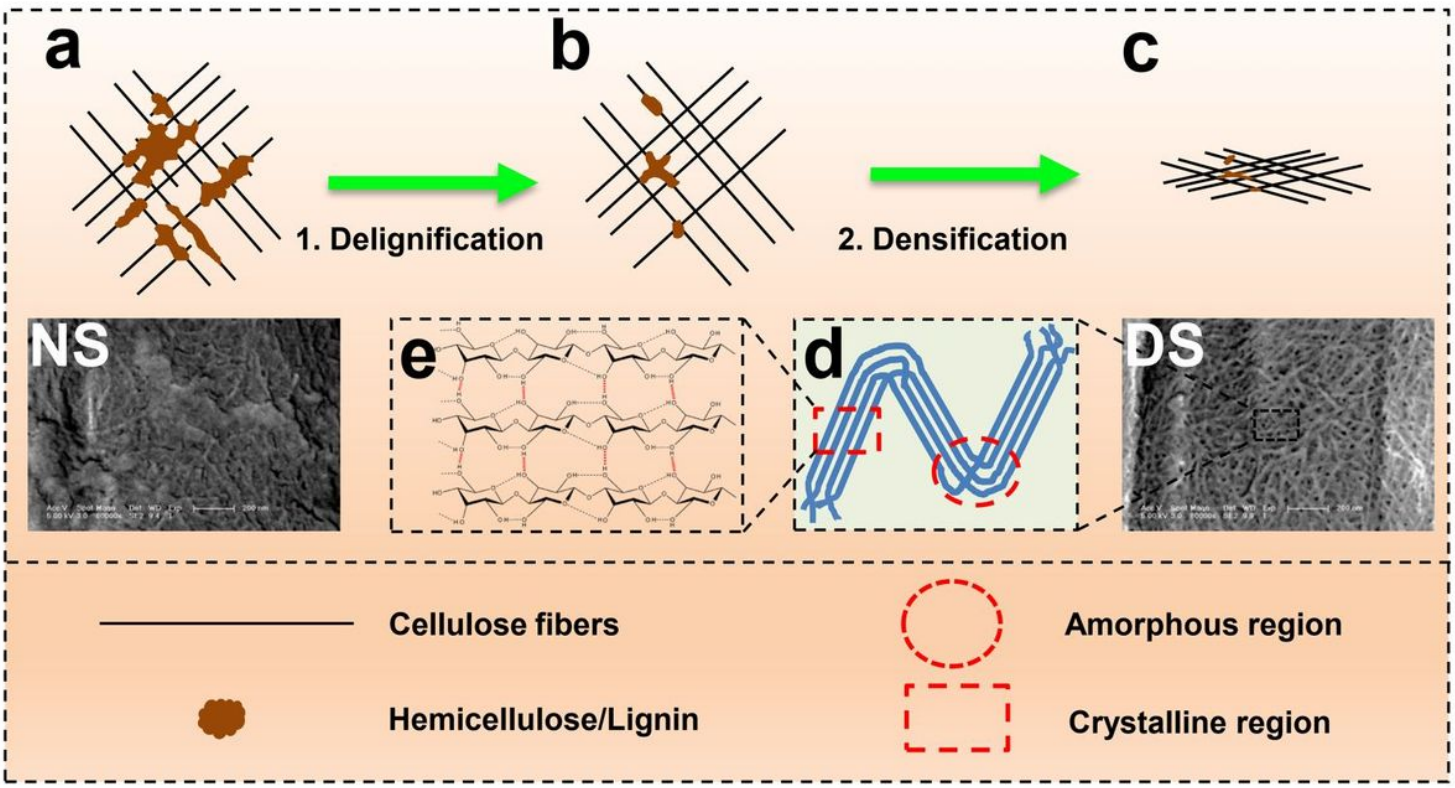

Figure 7

The changes of microfiber arrangement of natural straw (a), modified straw (b), and densified straw (c) during delignification and densification; the crystalline region and amorphous region of the cellulose microfibrils (d) and hydrogen bonds between cellulose molecules (e).

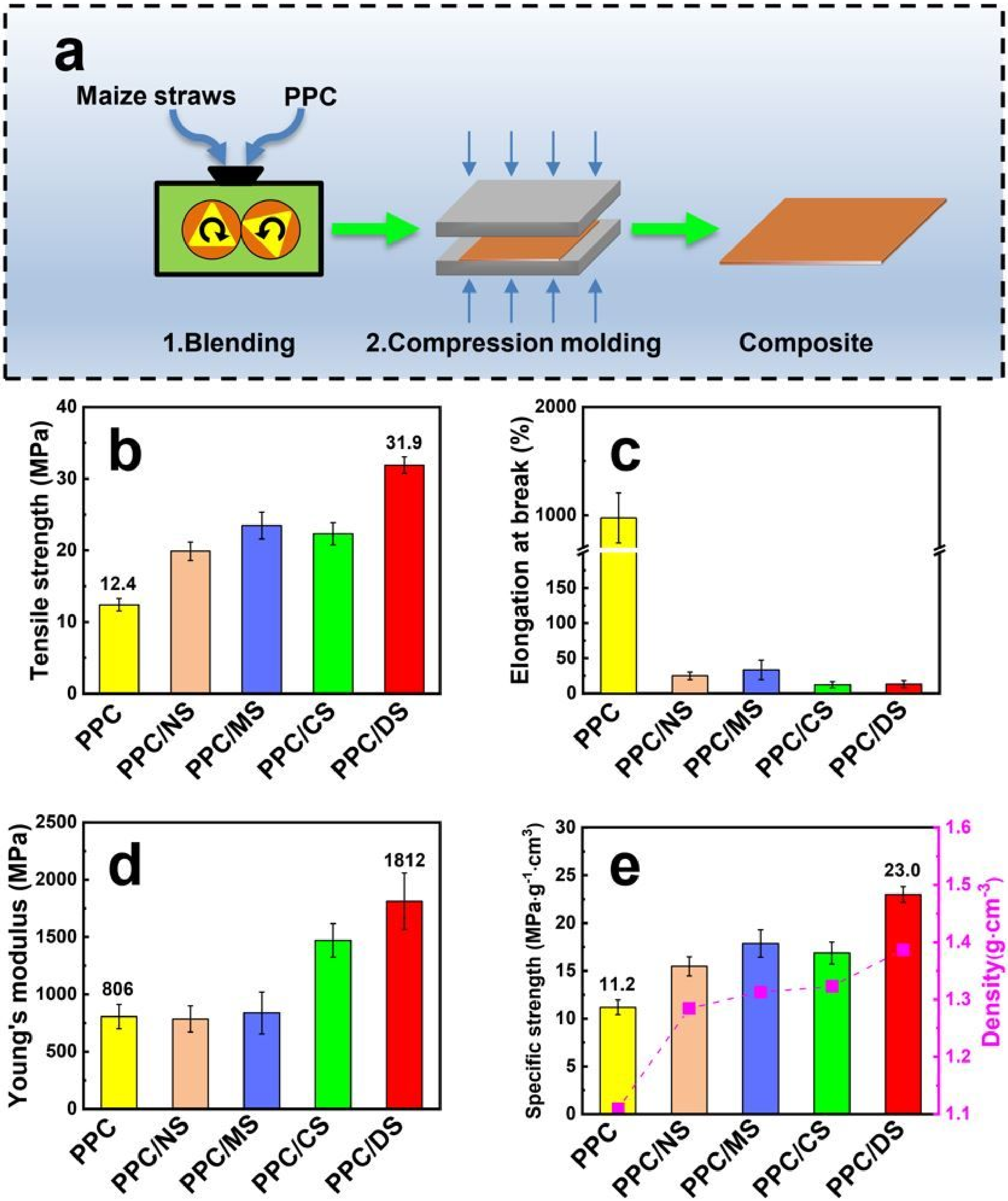

Figure 8

The process of fabricating the PPC/densified straw composite (a); the comparison of the tensile strength (b), elongation at break (c), Young's modulus (d), and specific strength and density (e) of the neat PPC and the composites of PPC/natural straw (PPC/NS), PPC/modified straw (PPC/MS), PPC/compressed straw (PPC/CS), and PPC/densified straw (PPC/DS).

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